DETERMINING THE EXPLOSIBILITY OF MINE ATMOSPHERES

BY M. G. ZABETAKIS, R. W. STAHL, AND H. A. WATSON

* * * * * * * * * **Information Circular 7901**

UNITED STATES DEPARTMENT OF THE INTERIOR
Fred A. Seaton, Secretary
BUREAU OF MINES
Marling J. Ankeny, Director

1959

The Library of Congress has cataloged this publication as follows:

Zabetakis, Michael George, 1924–
Determining the explosibility of mine atmospheres, by M. G. Zabetakis, R. W. Stahl, and H. A. Watson. [Washington] U. S. Dept. of the Interior, Bureau of Mines, 1959.

11 p. illus. 27 cm. (U. S. Bureau of Mines. Information circular 7901)

Bibliographical footnotes.

1. Mine gases. 2. Mine explosions. I. Title. (Series)

[TN295.U4 no. 7901] Int 59-52

U. S. Dept. of the Interior. Library
for Library of Congress

CONTENTS

Page

Summary and introduction.................................... 1

Acknowledgments.. 1

Explosibility diagram...................................... 1

Examples... 5

Maximum allowable oxygen................................... 9

ILLUSTRATIONS

Fig.

1. Explosibility diagram for methane-nitrogen-air mixtures at 80° F. and atmospheric pressure....... 2

2. Explosibility diagrams for methane-hydrogen-carbon monoxide-nitrogen-carbon dioxide-air mixtures..... 4

3. Explosibility diagrams for methane-hydrogen-carbon monoxide-nitrogen-carbon dioxide-air mixtures at 80° F. and atmospheric pressure with a sample composition point (example 1)..................... 7

4. Explosibility diagrams for methane-hydrogen-carbon monoxide-nitrogen-carbon dioxide-air mixtures at 80° F. and atmospheric pressure with a sample composition point (example 2)..................... 8

5. Explosibility diagrams for methane-hydrogen-carbon monoxide-nitrogen-carbon dioxide-air mixtures at 80° F. and atmospheric pressure with a sample composition point (example 3)..................... 10

DETERMINING THE EXPLOSIBILITY OF MINE ATMOSPHERES[1]

by

M. G. Zabetakis,[2] R. W. Stahl,[3] and H. A. Watson[4]

SUMMARY AND INTRODUCTION

This publication presents a simplified graphic method for determining the explosibility of mine atmospheres under mine-fire conditions from mine-atmosphere composition data.

Sometimes it is necessary to seal part of a mine during a fire to exclude air and thus extinguish the fire. Unfortunately, liberation of methane and formation of hydrogen and carbon monoxide in the sealed area may create an explosive or flammable atmosphere if enough oxygen is present to support combustion. On the other hand, the oxygen concentration may be reduced through combustion processes and the concentration of inert gases (nitrogen and carbon dioxide) increased enough to render the atmosphere within the sealed area nonexplosive. Before an area is unsealed, it is extremely important to know if the sealed atmosphere contains flammable gases in proportions that might form explosive mixtures when air is introduced. If an explosive mixture forms and the fire is rekindled, a gas explosion will result. Various experimental methods may be used to determine the explosibility of a particular mine atmosphere; however, these methods usually are impracticable in the field.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation of Bureau personnel, especially J. H. Dumire (deceased), A. E. Morrow, L. B. Berger, and G. S. Scott, who offered helpful advice and carefully weighed this simplified method of determining the explosibility of mine atmospheres.

EXPLOSIBILITY DIAGRAM

The method is based upon an explosibility diagram, such as that given in figure 1, for methane-nitrogen-air mixtures at 80° F. and atmospheric pressure.

---

[1] Work on manuscript completed February 1959.

[2] Chief, Branch of Gas Explosions, Division of Explosives Technology, Bureau of Mines, Pittsburgh, Pa.

[3] Mining health and safety engineer, Bureau of Mines, Pittsburgh, Pa.

[4] Chief, Gas Analysis and Research Section, Branch of Health Research, Bureau of Mines, Pittsburgh, Pa.

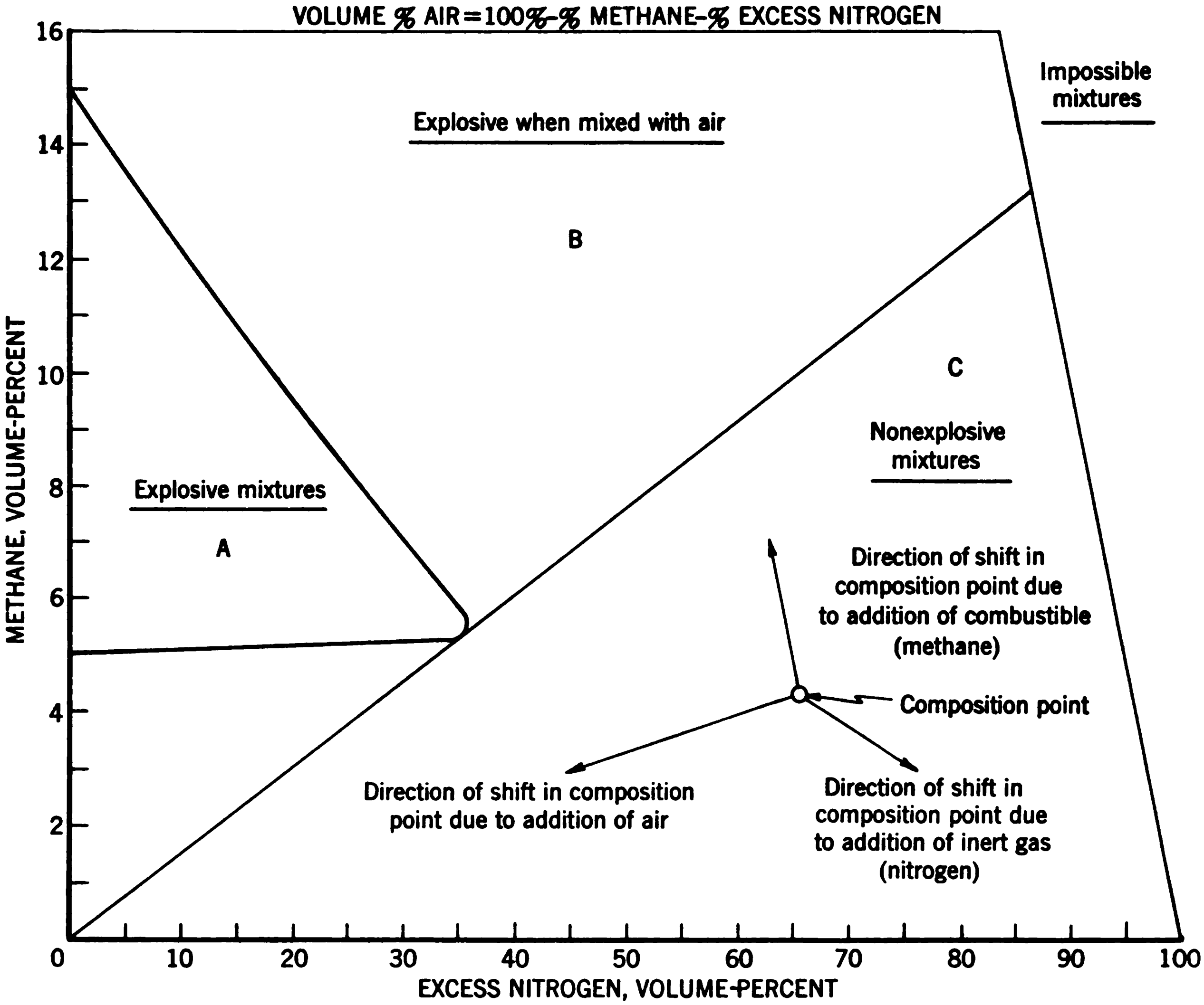


FIGURE 1. - Explosibility Diagram for Methane-Nitrogen-Air Mixtures at 80° F. and Atmospheric Pressure.

The diagram may be used to show at a glance whether any particular mixture of methane, nitrogen, and air is EXPLOSIVE (A), will become EXPLOSIVE WHEN MIXED WITH AIR (B), or is NONEXPLOSIVE (C). An EXPLOSIVE mixture may be ignited "as is"; therefore, it could cause a gas explosion. A mixture that will become EXPLOSIVE WHEN MIXED WITH AIR contains so much combustible gas and perhaps inert gas, such as carbon dioxide or nitrogen, that it is not explosive; however, it would form explosive mixtures upon the addition of air. A NONEXPLOSIVE mixture contains either so much inert gas or so little combustible gas that it cannot be ignited "as is"; furthermore, it will not form explosive mixtures when air is added.

In practice, the composition of the gases in a sealed area may vary with time, so that a nonexplosive mixture may become explosive or an explosive mixture may become nonexplosive because of generation, addition, or consumptior of gases within the sealed area. For a given situation, the composition of gases can be represented by a point (Composition Point) on an explosibility diagram. Figure 1 shows a Composition Point in the NONEXPLOSIVE region. As noted in the figure, the addition of any of the constituent gases to the original gas mixture would cause the Composition Point to shift position; that is, the addition of (1) combustible alone, (2) inert alone, or (3) air alone would shift the Composition Point along the line joining this point to that representing (1) 100 percent combustible, 0 percent inert, 0 percent air; (2) 0 percent combustible, 100 percent inert, 0 percent air; or (3) 0 percent combustible, 0 percent inert, 100 percent air, respectively.

Mine-fire atmospheres often contain hydrogen and carbon monoxide in addition to methane, air, carbon dioxide, and excess nitrogen (that is, nitrogen in excess of that in the air). Accordingly, the explosibility diagram (fig. 1) must be expanded to include these additional gases. Such a series of diagrams (fig. 2) has been constructed for mine atmospheres containing a maximum of 5 percent hydrogen and 3 percent carbon monoxide. Mine atmospheres containing more than these quantities of hydrogen and carbon monoxide should be evaluated using the more detailed procedure outlined by Jones.[5]

As methane, hydrogen, and carbon monoxide do not have the same lower limits of flammability[6] (or explosibility), appropriate conversion factors are used in figure 2 to give the same effective lower limits for each gas. Similarly, carbon dioxide and nitrogen are not equally effective in producing nonflammable mixtures, so appropriate conversion factors must be used to calculate an effective inert-gas concentration. The conversion factors used in this report do not take into account the difference in inert-gas requirements of hydrogen and carbon monoxide; the maximum requirements were used to construct the curves in figure 2. Accordingly, these curves present a small factor of safety when used at ordinary temperatures. This factor of safety disappears if the gas mixture in question contains very little carbon monoxide or if the temperature of the mixture is high. Actually, mine-atmosphere temperatures likely to be encountered during recovery work would have little effect on these curves.

The use of the explosibility diagrams (fig. 2) to determine the explosibility of a mine atmosphere depends upon converting the methane, hydrogen, and carbon monoxide in the atmosphere to an effective combustible content and the carbon dioxide and nitrogen to an effective inert content. These concentrations then determine the Composition Point on the explosibility diagram, and the ratio R of methane (CH_4) to total combustibles ($CH_4 + H_2 + CO$) determines the explosibility curve to be used in figure 2. These curves are labeled 1.0, 0.8, 0.6, 0.4, 0.2, and 0. Curve 1.0 applies to a mine atmosphere that contains neither hydrogen nor carbon monoxide; that is, methane is the only combustible gas in the mixture, and the explosive mixtures are those with Composition Points lying in area A_1. Curve 0.8 applies to a mine atmosphere that

---

[5] Jones, G. W., Inflammability of Mixed Gases: Bureau of Mines Tech. Paper 450, 1929, 38 pp.

[6] Coward, H. F., and Jones, G. W., Limits of Flammability of Gases and Vapors: Bureau of Mines Bull. 503, 1952, 144 pp.

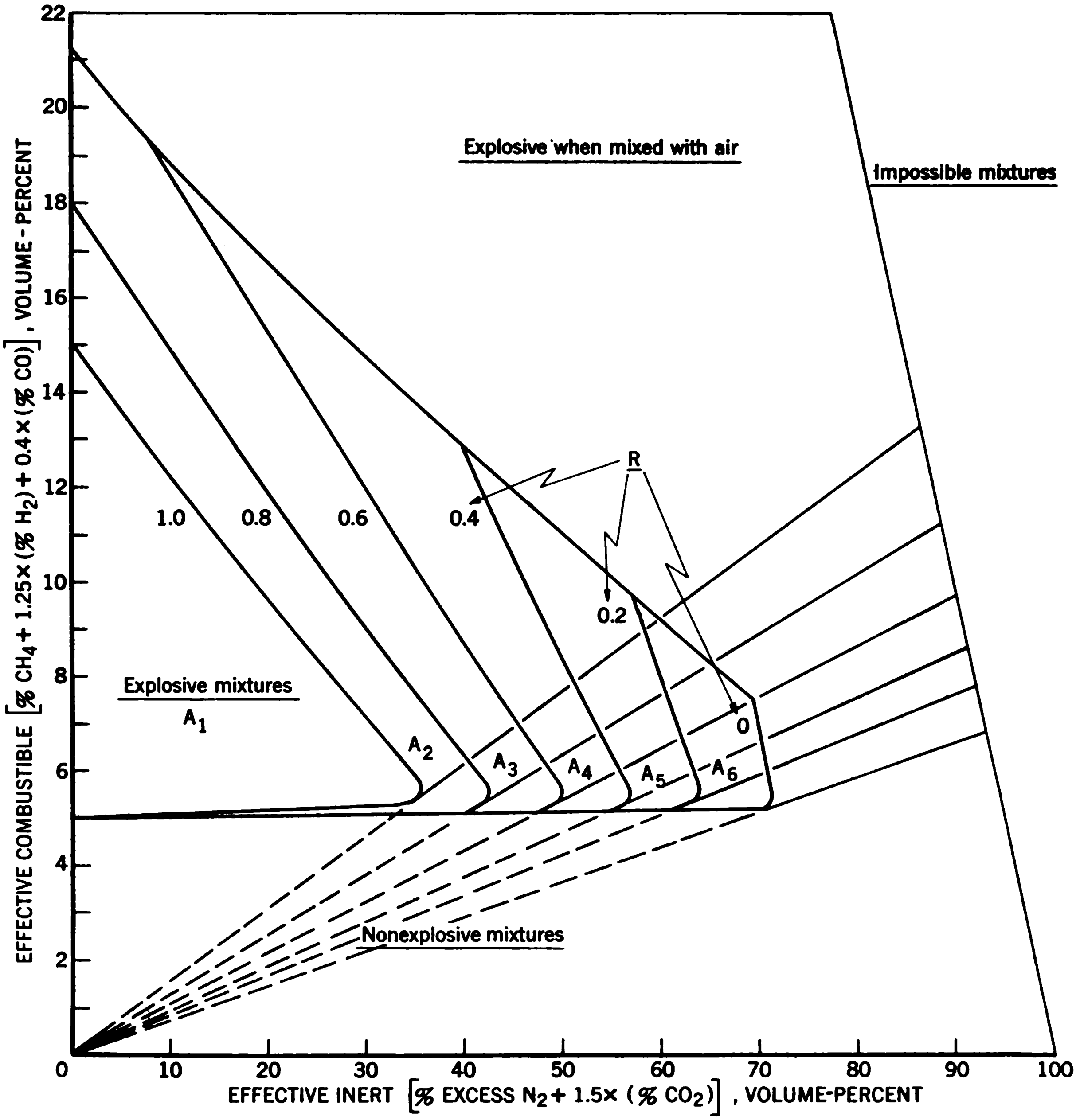


FIGURE 2. - Explosibility Diagrams for Methane-Hydrogen-Carbon Monoxide-Nitrogen-Carbon Dioxide-Air Mixtures.

contains four times as much methane as hydrogen plus carbon monoxide, and the explosive mixtures are those with Composition Points lying in areas A_1 and A_2. Curve 0.6 applies to a mine atmosphere that contains 1.5 times as much methane as hydrogen plus carbon monoxide, and the explosive mixtures are those with Composition Points lying in areas A_1, A_2, and A_3, etc. Curve 0 applies to a mine atmosphere that does not contain methane; that is, it contains only hydrogen and carbon monoxide in addition to air and inert gases. Curves representing intermediate methane-to-total-combustible ratios may be constructed as noted in figures 3 and 5. For example, the curve for a ratio of 0.5 ($\underline{R} = 0.5$) would fall midway between the curves, $\underline{R} = 0.4$ and $\underline{R} = 0.6$.

Briefly, the following steps may be used to obtain the *Composition Point* (Effective Inert, Effective Combustible) in figure 2:

1. Analyze the mine atmosphere,[7] determining percentages, by volume, of carbon dioxide (CO_2), oxygen (O_2), carbon monoxide (CO), methane (CH_4), hydrogen (H_2), and nitrogen (N_2).

2. Calculate the percentages of excess nitrogen and *Effective Inert* as follows:

Percent excess N_2 = % N_2 in sample - % normal N_2

where

percent N_2 in sample = 100% minus (% CO_2 + % O_2 + % CO + % CH_4 + % H_2) and

percent normal N_2 = 3.8 x % O_2 in sample.

(The factor 3.8 is the volume ratio of N_2 to O_2 in normal air.)

Effective Inert = % excess N_2 + 1.5 x (% CO_2).

3. Calculate percent *Effective Combustible* as follows:

Effective Combustible = % CH_4 + 1.25 x (% H_2) + 0.4 x (% CO).

(The factors 1.25 and 0.4 are, respectively, the ratios of the lower explosive limits of CH_4 to that of H_2 and CO.)

4. Calculate the ratio of CH_4 to total combustible ($\underline{R}$) to determine the explosibility curve to be used.

EXAMPLES

Example 1: The following gas analysis was obtained after a mine fire. The *Composition Point* was determined as shown:

Gas	Concentration, percent by volume	
CO_2	10.9	25.3
O_2	7.3	
CO	2.9	
CH_4	1.1	
H_2	3.1	
N_2	74.7	= 100 - 25.3

---

[7] Berger, L. B., and Schrenk, H. H., Sampling and Analysis of Mine Atmospheres, Bureau of Mines Miners' Circ. 34, rev., 1948, 103 pp.

Percent excess N_2 = 74.7 - (3.8 x 7.3) = 47.0.

Effective inert = 47.0 + (1.5 x 10.9) = 63.4%.

Effective combustible = 1.1 + (1.25 x 3.1) + (0.4 x 2.9) = 6.2%.

Total combustible = 1.1% + 3.1% + 2.9% = 7.1%.

$$\underline{R} = \frac{1.1}{7.1} = 0.15.$$

(This corresponds to an explosibility diagram approximately three-fourths the distance between the 0 and 0.2 curves in fig. 2.)

In figure 3, Effective Inert is plotted on the horizontal axis and Effective Combustible on the vertical axis to arrive at the Composition Point shown in example 1. As this point lies just within the EXPLOSIVE region for the 0.15 methane-to-total combustible flammability curve, the mine atmosphere should be considered explosive. At ordinary mine temperatures this Composition Point would lie just outside the explosive region but inside the region where an explosive mixture would be formed upon addition of air; however, as the temperature within a mine in which a fire has occurred may be higher than normal, it is well to consider such a borderline composition explosive.

Example 2: The following gases were obtained from a sealed coal-mine fire area:

Gas	Concentration, percent by volume	
CO_2	1.0	22.8
O_2	17.1	
CO	.03	
CH_4	4.7	
H_2	.0	
N_2	77.2 = 100 - 22.8	

These figures may be used to define the Composition Point and $\underline{R}$ as follows:

Percent excess N_2 = 77.2 - (3.8 x 17.1) = 12.2.

Effective Inert = 12.2 + (1.5 x 1.0)
= 12.2 ± 1.5 = 13.7%.

Effective combustible = 4.7 + (0.4 x 0.03)
= 4.7 + 0.01 = 4.71%.

Total combustible = 4.7 + 0.03 = 4.73%.

$$\underline{R} = \frac{4.7}{4.73} = 1.0.$$

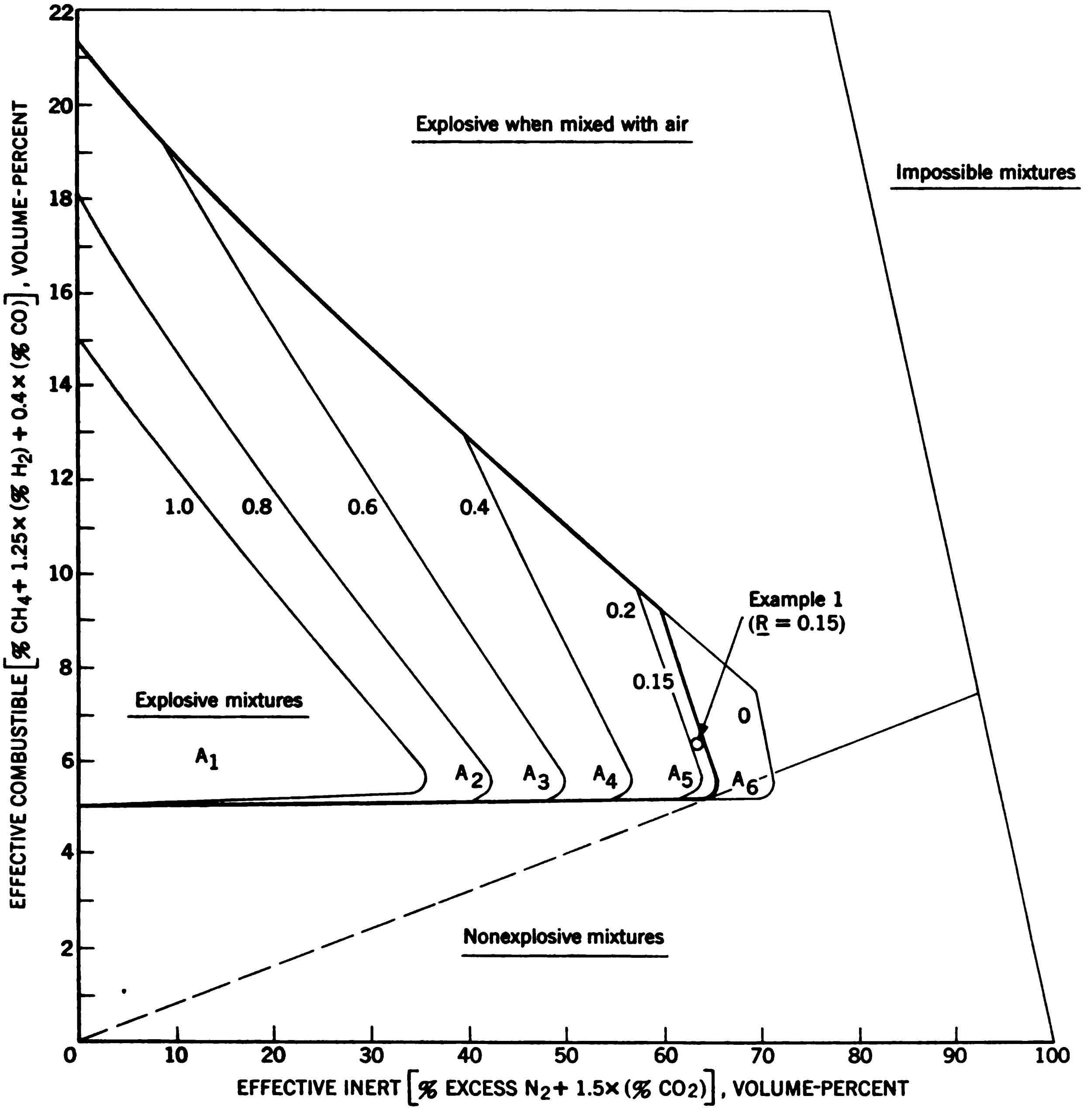


FIGURE 3. - Explosibility Diagrams for Methane-Hydrogen-Carbon Monoxide-Nitrogen-Carbon Dioxide-Air Mixtures at 80°F. and Atmospheric Pressure With a Sample Composition Point (Example 1).

In figure 4, Effective Inert is plotted on the horizontal axis and Effective Combustible on the vertical axis to arrive at the Composition Point shown in example 2. In this example, the Composition Point lies just below the explosive region. The addition of air or inert gas (or both) will not make the mixture explosive; however, a small increase in the combustible or the

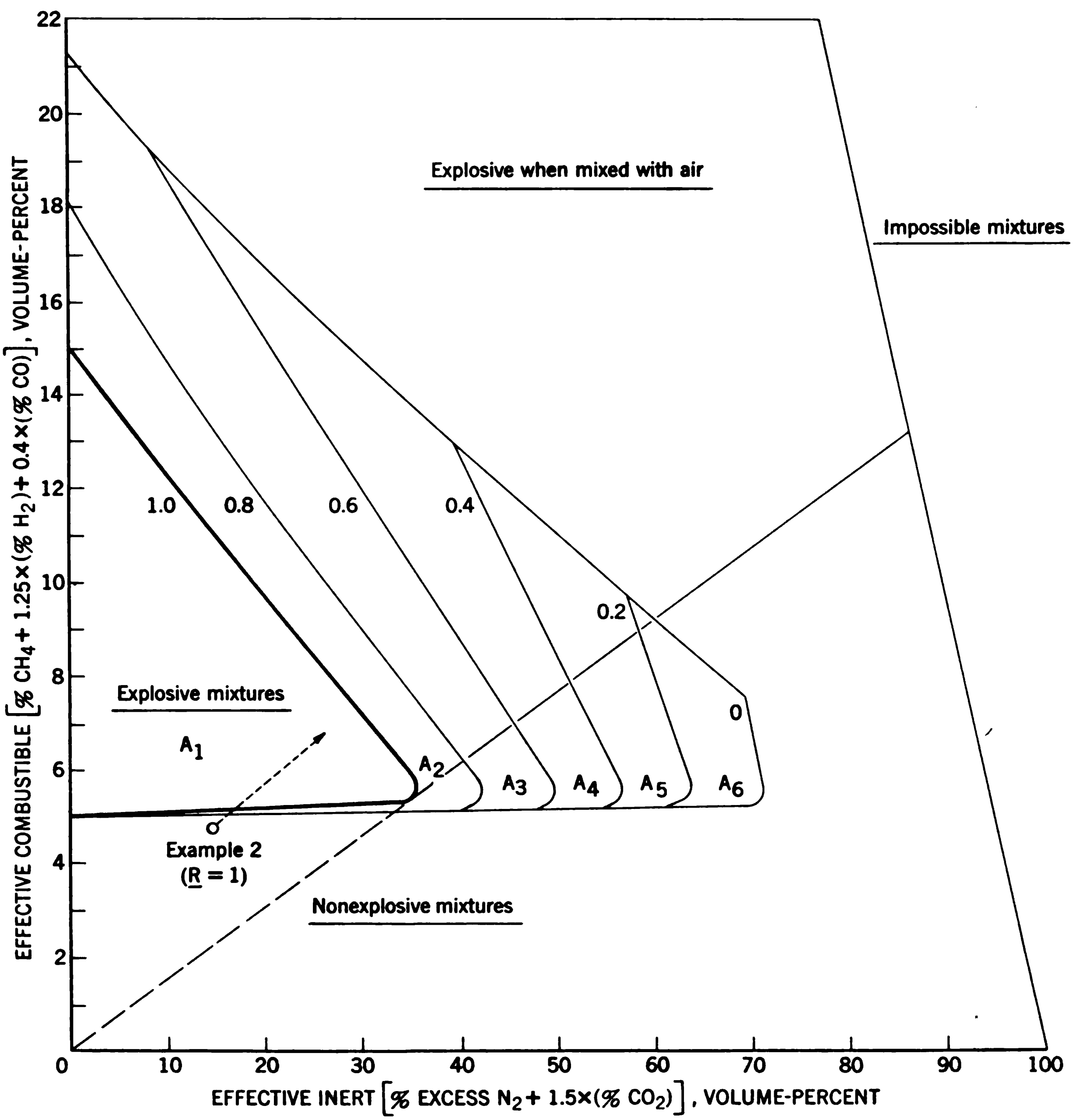


FIGURE 4. - Explosibility Diagrams for Methane-Hydrogen-Carbon Monoxide-Nitrogen-Carbon Dioxide-Air Mixtures at 80°F. and Atmospheric Pressure With a Sample Composition Point (Example 2).

temperature would tend to make the mixture explosive. Subsequent samples showed that the Composition Point actually shifted into the EXPLOSIVE region along the path indicated by the arrow. This shift was caused by the liberation and partial combustion of methane.

Example 3: The following gases were found in a sealed area following a mine fire:

Gas	Concentration percent by volume	
CO_2	16.5	28.1
O_2	.9	
CO	2.1	
CH_4	3.9	
H_2	4.7	
N_2	71.9 = 100 - 28.1	

These values yield:

$$\text{Percent excess } N_2 = 71.9 - (3.8 \times 0.9)$$
$$= 71.9 - 3.4 = 68.5.$$

$$\text{Effective Inert} = 68.5 + (1.5 \times 16.5)$$
$$= 68.5 + 24.8 = 93.3\%.$$

$$\text{Effective Combustible} = 3.9 + (0.4 \times 2.1) + (1.25 \times 4.7)$$
$$= 3.9 + 0.8 + 5.9 = 10.6\%.$$

$$\text{Total combustible} = 3.9 + 2.1 + 4.7 = 10.7\%.$$

$$\underline{R} = \frac{3.9}{10.7} = 0.36.$$

In figure 5, the Effective Inert is plotted on the horizontal axis and Effective Combustible on the vertical axis to arrive at the Composition Point shown in example 3. This Composition Point lies in the Impossible Mixtures region so that the mixture is NONEXPLOSIVE, but it would become EXPLOSIVE upon addition of air. Subsequent samples showed that the Composition Point shifted into the NONEXPLOSIVE region, as indicated by the arrow.

Example 3 was included to show that the combination, percentage of excess nitrogen plus 1.5 (percentage of CO_2), can lead to Composition Points in the Impossible Region because of the factor, 1.5, by which the carbon dioxide content is multiplied. In this example, the quantity of inert gas is enough to render the mixture NONEXPLOSIVE.

The preceding examples show that analytical data obtained from sealed mine-fire areas may be used to determine the explosibility of the atmosphere within the sealed area quite readily and to determine the trends in the explosibility of such atmospheres. With a little practice, the Composition Point on figure 2 of any atmosphere can be located in approximately 1 minute.

MAXIMUM ALLOWABLE OXYGEN

The quantity of oxygen required for flame propagation, therefore the maximum allowable oxygen (maximum O_2), depends on the relative quantities of methane, carbon monoxide, and hydrogen in the mine-fire area. When the oxygen

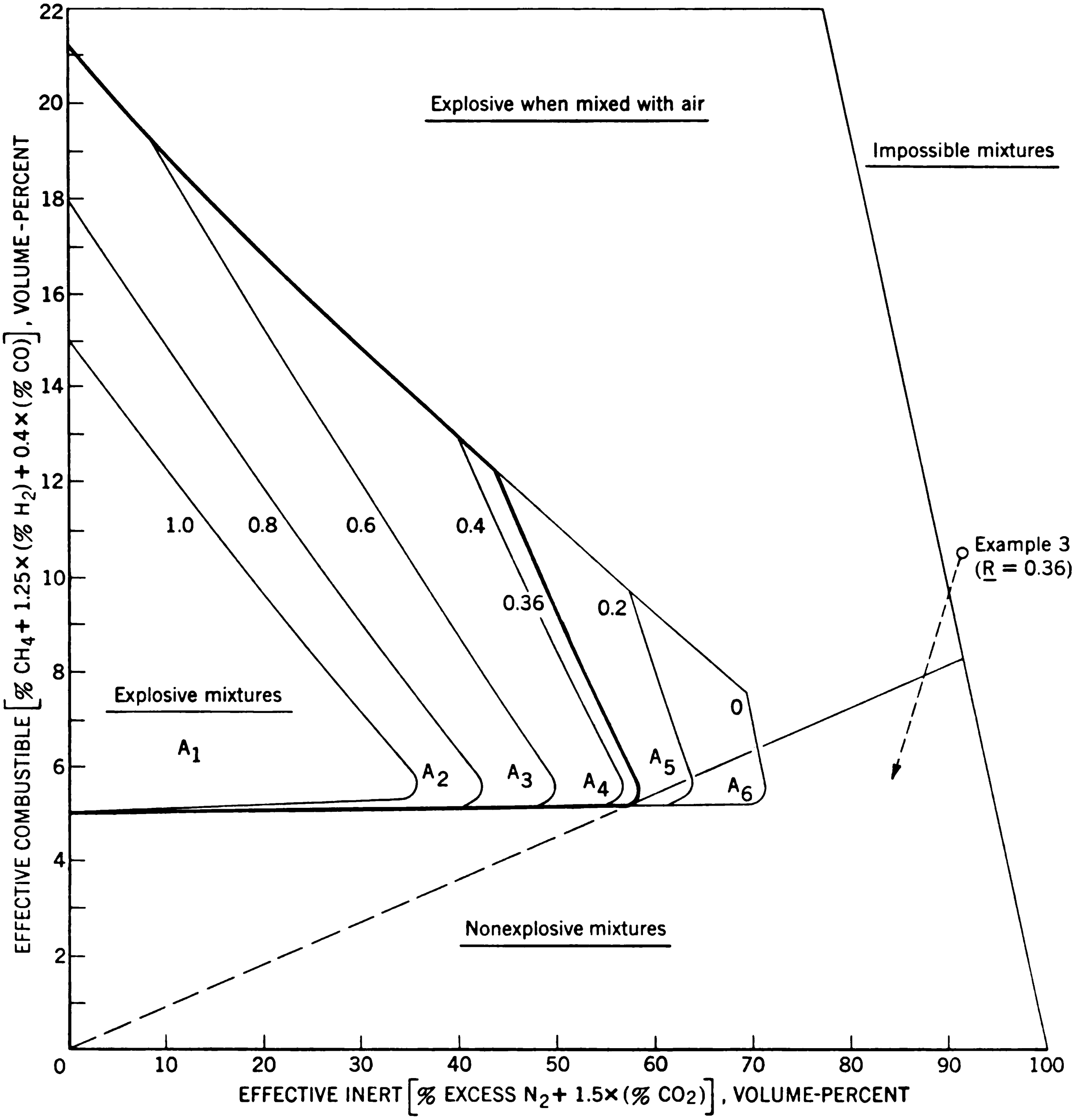
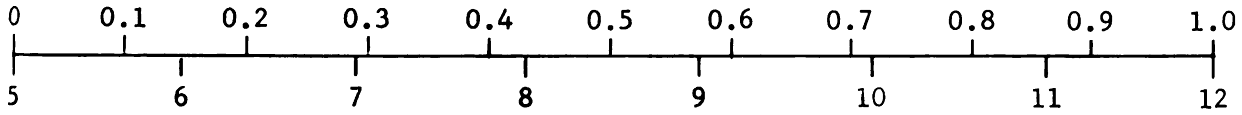


FIGURE 5. - Explosibility Diagrams for Methane-Hydrogen-Carbon Monoxide-Nitrogen-Carbon Dioxide-Air Mixtures at 80°F. and Atmospheric Pressure With a Sample Composition Point (Example 3).

concentration in a mixture is below the specified maximum O_2 value, the mixture is either NONEXPLOSIVE or EXPLOSIVE WHEN MIXED WITH AIR. Accordingly, a mixture can often be assessed readily by noting its oxygen content and methane-to-total-combustible ratio ($\underline{R}$). If the Maximum O_2 value corresponding to $\underline{R}$ is not exceeded, the mixture cannot be ignited "as is"; however, if the maximum O_2 value is exceeded, this method is not applicable and the explosibility of the mine atmosphere must be determined with the aid of the explosibility diagram.

The following ratio scale can be used to tell at a glance the maximum allowable oxygen concentration as a function of the methane-to-total combustible ratio, R.

$$\underline{R} = \frac{\%\ CH_4}{\%\ CH_4 + \%\ H_2 + \%\ CO}$$



Maximum O_2.

If desired, the maximum O_2 value can also be obtained from the expression:

$$\text{Maximum } O_2 = 5.0 + 7\ \underline{R}.$$

The R values in the preceding examples were 0.15, 1.0, and 0.36; these correspond to maximum allowable oxygen concentrations of 6.1, 12, and 7.5 volume-percent, respectively. The measured oxygen concentrations were 7.3, 17.1, and 0.9 volume-percent, respectively. Thus, the actual oxygen concentration was less than the allowable concentration only in the last example, which was found to be nonflammable. However, in the first two examples, the oxygen concentration must be reduced by 1.2 and 5.1 volume-percent, respectively, so that it will not exceed the allowable maximum.